An Inter Planetary Network Enabled by SmallSats

Jose Velazco
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Jose.E.Velazco@jpl.nasa.gov

Abstract—**This paper describes the implementation of an unparalleled large sensor and communications platform along the solar system that we call the inter planetary network (IPN). The proposed IPN consists of thousands of small spacecraft (e.g. CubeSats) strategically deployed around planetary bodies in the solar system where each spacecraft is furnished with fast communications and sensor systems. The IPN concept is being proposed as an avant-garde science and communications platform that could allow for continuous fast communications and remarkable science returns. The IPN spacecraft, furnished with suitable miniaturized sensors, could form an amazing deep space platform for unique observation of the solar system, stars, galaxies and universe. A key feature of the IPN architecture is the use of swarms of spacecraft as network units. Super-high-speed intra-swarm communications could be achieved via omnidirectional optical links. The swarms act as autonomous network nodes and are capable of forming large synthetic apertures that enable high data rate communications among the IPN nodes. Depending on the sensors they carry, these swarms may also be capable of forming large synthetic sensors by rapidly combining data among the spacecraft. We envision distances between spacecraft forming a swarm to be in the range of 10^2-10^4 kilometers, whereas distances of 10^6-10^8 kilometers among swarms (IPN nodes) are expected. We provide an example of an initial IPN implementation in the inner solar system where swarms of spacecraft are deployed around the Earth, Moon, Mars, Venus and Mercury. Placing swarms around 3 Lagrange points per planet yield a total of 12 possible IPN network nodes. We present communications link calculations among IPN nodes that allow high data rate communications between Earth and Mars while Mars is in solar conjunction (behind the Sun). A second example of an IPN platforms includes a giant spaceborne radio telescope behind the moon.**

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1. INTRODUCTION

Typical space missions involve single flagship spacecraft furnished with a suite of sensors and communications system that cost up to $1B [1-2]. The science data generated by these missions is typically downlinked directly from the spacecraft to ground stations in the Deep Space Network [3] via X-band or Ka-band links. These flagship missions tend to be seasonal and include large communications systems to transmit their data back to Earth.

In this paper we introduce a paradigm shift in the way space missions could be carried out. The proposed inter planetary network (IPN) involves the implementation of a spaceborne platform that includes hundreds to thousands of small spacecraft placed along the solar system. The IPN spacecraft would be small (e.g. CubeSats), affordable and could include integrated propulsion, telecommunications and sensor payloads.

A key enabler for implementing the IPN is the use of the Inter Planetary Superhighway [4]. The Inter Planetary Superhighway is a collection of gravitationally determined pathways through the Solar System that require very little energy for a spacecraft to follow. The Inter Planetary Superhighway makes particular use of Lagrange points as locations where trajectories through space are redirected using little or no energy. For example, low energy orbits were used by engineers from the Jet Propulsion Laboratory (JPL) and the Japanese Space Agency to enable the Japanese Hiten mission to reach the Moon [5]. The IPN would make use of this Superhighway to transport swarms of small spacecraft from low Earth orbit LEO (or geosynchronous transfer orbit, GTO) to Lagrange points near the Moon, Mars, Jupiter and other planets (see Fig. 1). Lagrange points are positions within a planet's orbit around the Sun where the combined gravitational force of the Sun and the planet provides the exact centripetal force needed for a spacecraft to orbit the Sun at the same rate as the planet (Fig. 2). The primary mission of the IPN spacecraft swarms is to act as highway "cell towers" that relay information from assets orbiting planets (or located on planetary surfaces) to Earth. In addition, the IPN swarms are to be furnished with suitable sensors to form a remarkably large science platform for observing the universe. Among the giant "synthetic" instruments that the IPN can enable are radio telescopes (for observing radio emissions from stars, galaxies and exoplanets), Gamma-ray burst detectors (detectors work in unison to locate gamma-ray bursts through triangulation), optical telescopes, helio physics analyzers (solar isotope spectrometers, electric field meters, magnetometers, particle detectors), etc., which would feature enormous baselines that could yield unparalleled angular resolution in observation. The intra- and inter-swarm distances vary from tens of kilometers to astronomic units.

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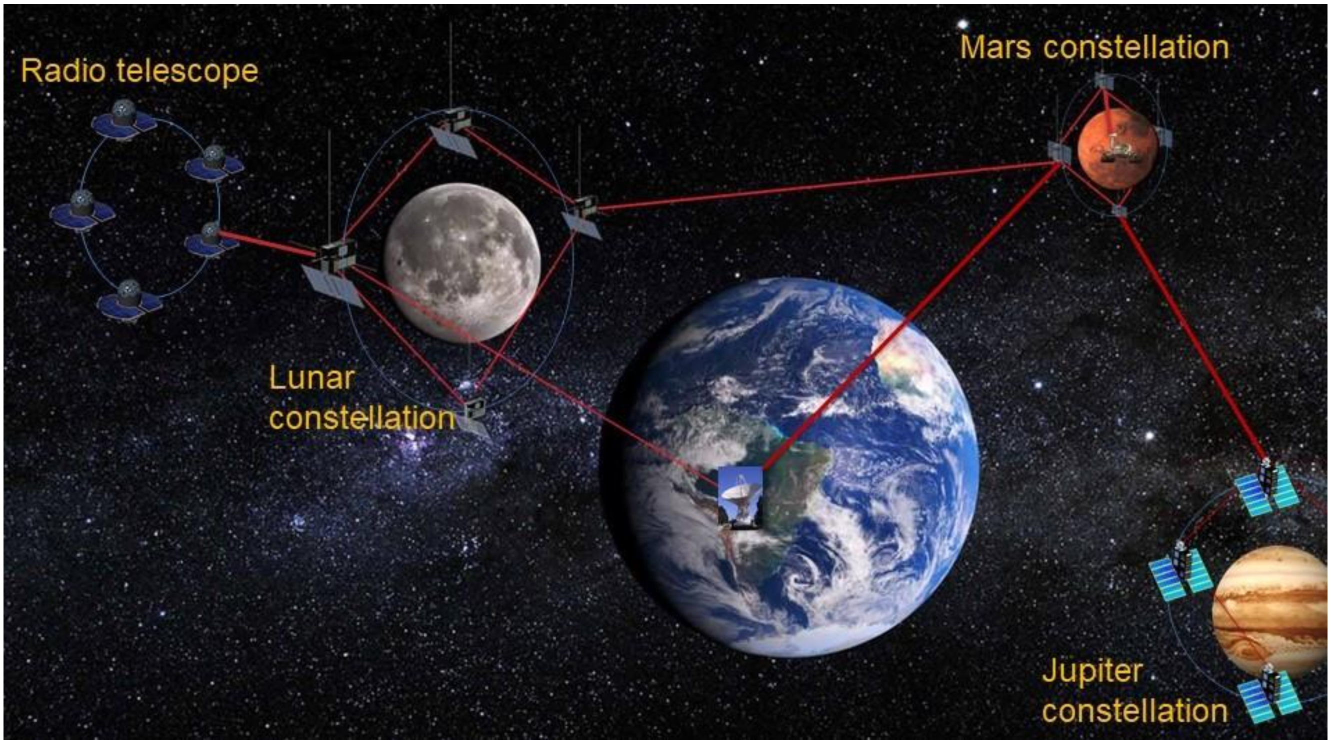

Figure 1. Inter-planetary Network concept showing a large number of small spacecraft deployed along the solar system. This embodiment of the IPN includes constellations of spacecraft around the Moon, Mars and Jupiter as well as a radio telescope behind the moon.

Such distances should allow the IPN sensors to generate unique spatio-temporal science measurements.

The implementation of the proposed IPN would be gradual and continuous, and shall require a sustained effort from engineers and scientists. The IPN platform would be unrivaled in size and scientific return and its construction could be pursued in a Lego-like approach where sorties of affordable spacecraft are periodically deployed in space to gradually form this unique inter planetary communications and scientific network. The IPN builds on the successful inter planetary voyage of MarCO [6]. Another key feature of the IPN is graceful degradation, where obsolete or broken spacecraft could be replenished in a timely manner.

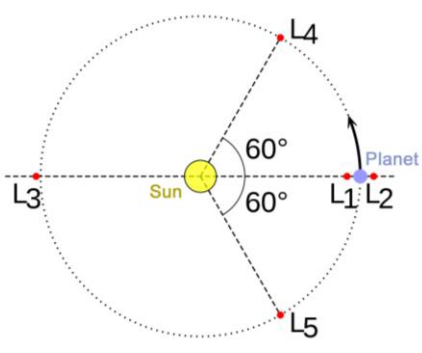

Figure 2. Five Lagrange points (L1-L5) between the Sun and a planet.

Additional key features of the IPN include: 1) the use of a standard and affordable spacecraft (e.g. CubeSats), 2) the use of swarms as building block units, 3) dual use (science and communications), 4) use of miniaturized sensors, 5) high inter-/intra-swarm data rate communications and 6) fully-networked.

Section 2 provides a general description of the IPN. Section 3 describes the IPN architecture. Potential science return cases are described in Section 4. Section 5 describes the IPN CADRE radio telescope and the inner solar system IPN is discussed in Section 6. Section 7 provides a summary.

2. DESCRIPTION

This paper describes the implementation of an inter planetary platform formed by thousands of spacecraft deployed across the solar system. The proposed IPN features dual-use capabilities. First, it is meant to be a multi-sensor platform whereby the various IPN spacecraft are furnished with scientific sensors. Second, all the IPN spacecraft are to be interconnected via optical communications systems to relay science and telemetry information back to Earth.

The IPN exhibits a flexible architecture where each new mission can become a new network node. As long as a new mission carries the proper communications payload and software protocols (e.g. DTN [7]), they could be added as new IPN nodes. The IPN nodes could be single flagship spacecraft or swarms of small spacecraft.

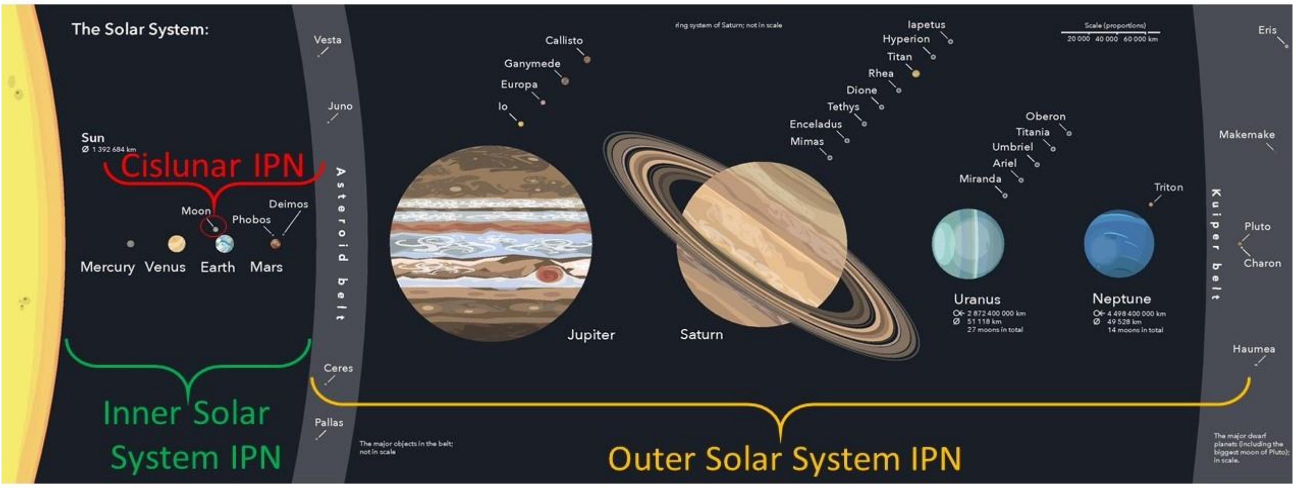

Figure 3. The Inter-planetary Network would be distributed along the solar system as shown in this image. There are three distinct parts of the IPN: Inner Solar System IPN, Outer Solar System IPN and Cislunar IPN.

IPN Classification

The implementation of the IPN would be gradual and continuous. We envision the IPN to consist of 3 main sub-networks: cislunar IPN (CL-IPN), inner solar system IPN (ISS-IPN) and outer solar system IPN (OSS-IPN) (Fig. 3). All the sub-networks are to be fully networked and connected to Earth. NASA's current strategy includes the implementation of the lunar gateway orbiter and possibly lunar ground assets, such as rovers and other instruments, as a stepping stone towards manned Mars missions. As part of the cislunar IPN, in addition to the gateway, we are also considering the placement of a lunar radio telescope around L2 (Earth-Sun Lagrange point) and a constellation of lunar orbiting smallsats for fast communications between the lunar gateway and surface assets. We foresee the gateway to be the main communication relay between lunar assets and Earth ground stations.

The ISS-IPN consists of orbiting swarms around Mercury, Venus, Earth and Mars (including its moons). Spacecraft fleets around Jupiter, Saturn, Neptune and Uranus are considered as part of the OSS-IPN.

3. IPN ARCHITECTURE

The IPN is being proposed as a unique solar system platform and communications framework consisting of thousands of spacecraft that could provide a massive sensor and communications network. The IPN should be able to provide an entirely new level of science return (e.g., radio telescopes with multi-astronomic unit baselines) via its communications backbone. For example, communications spacecraft can be inserted into stable orbits around the Earth- and Venus-Sun Lagrange points to establish high speed communications nodes between Earth and Mars. Spacecraft located around L4 and L5 points allow continuous communication with Mars even when Mars is in conjunction. Another application we envision for the IPN could be the placement of hundreds of CubeSats in Lunar orbit (via the Inter planetary Superhighway) whereby CubeSats, furnished with miniature High-Frequency receivers, could detect magnetospheric exoplanets (possibly sustaining life) via radiofrequency emissions. Yet another application allowed by the IPN swarms could be three-dimensional studies of the interaction between Earth's magnetosphere and the "solar wind" of charged particles streaming off the sun.

The Inter planetary Superhighways allows the systematic placement of spacecraft swarms on various planetary Lagrange points to gradually form the inter planetary network. Using existing simulation tools, we should be able to determine launching schedules and low-energy orbits to populate the selected Lagrange points.

Cubesat Unit

A key approach for successful IPN implementation is the use of affordable small spacecraft. We are considering the use of 6U CubeSats with standardized components. Each IPN CubeSat includes a BlueCanyon XACT attitude determination and control system (ADCS) [8] and an eHawk 72W solar power by MMA [9] (see Fig. 4). The eHawk solar panel is currently being used for many high profile missions such as JPL's MarCO [6], Asteria [10], Lunar Flashlight [11], NASA's BioSentinel [12], NEAScout [13], and ASU's LunaH-Map [14]. The IPN CubeSats also include a MiPS cold gas thruster. In addition, the 6U CubeSats would have sufficient room (~2U) to house miniaturized science sensors.

IPN Communications

Before we continue we would like to introduce several basic equations to evaluate communication data rates along the IPN network. The maximum data rate r_b (in bits per second) between two communications terminals (see Fig. 5) can be determined by the Shannon limit as,

$$r_b = B \cdot log_2\left(1 + \frac{P_r}{P_N}\right) \qquad (1)$$

where B is the system bandwidth, P_r is the received power

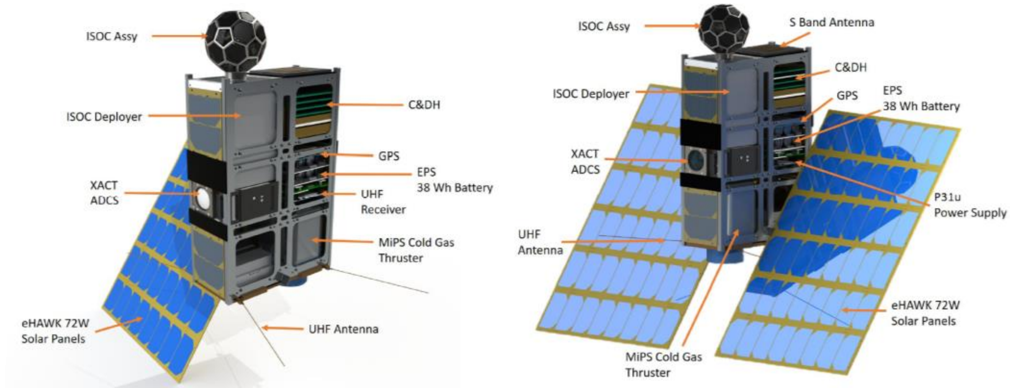

Figure 4. 6U CubeSats are be the basis for the Inter-planetary Network swarms. Each CubeSat includes an optical communicator, attitude determination and control system, electric power system and solar panels. They also carry miniaturized sensors.

given by,

$$P_r = P_t \left(\pi \frac{D_t}{\lambda}\right)^2 \left(\pi \frac{D_r}{\lambda}\right)^2 \left(\frac{\lambda}{4\pi R}\right)^2 \qquad (2)$$

and P_N is the noise power in the receiving system,

$$P_N = \begin{cases} hcB/\lambda, & Optical\ system \qquad (3a) \\ kT_{sys}B, & RF\ system \qquad (3b) \end{cases}$$

Here P_t is the transmitted power, D_t and D_r are, respectively, the transmit and receive aperture diameters, λ is the operating wavelength and R is the distance between terminals. Where k is the Boltzmann's constant, T_{sys} is the effective system temperature of the receiver, h is Planck's constant, and c is the speed of light.

It is also important to introduce an expression for the optical beam diameter, D_b^o, as a function of distance z from the transmitter:

$$D_b^o = \theta_d z \qquad (4)$$

where $\theta_d = 4\lambda/(\pi D_t)$ is the optical beam divergence angle. The optical beam diameter increases linearly with *z*. Note also that in order to avoid excessive beam spreading, the divergence angle should be minimized (typically by optimizing the diameter of the transmit aperture). For instance, assuming a $\theta_d = 2\ \mu rad$, the optical beam diameter at a distance of 200 km would be 4 meters whereas the beam would spread to a diameter of 3,000 km at a 1 astronomic unit (1 AU = $150 \cdot 10^6$ km) distance.

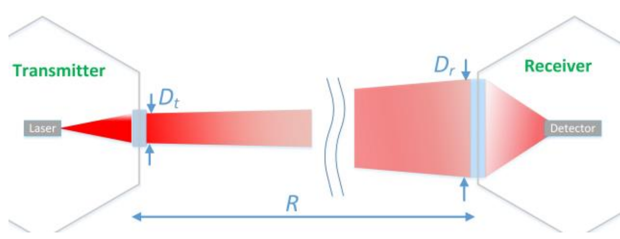

Figure 5. Transmitter and receiver terminals showing relevant parameters for IPN optical communications.

Cubesat Swarm

As indicated earlier, the proposed IPN is based on swarm units similar to the one shown in Fig. 6. A swarm unit consists of one mothership (or more) and several daughterships. We envision spacecraft being furnished with JPL's inter-spacecraft omnidirectional optical communicators (ISOC) [15-18] and forming clusters that could operate autonomously as a single sensor and communications unit. (An image of the ISOC is shown in Fig. 7.) The spacecraft swarm equipped with ISOCs and high resolution sensors could act as a larger synthetic sensor (this is discussed in more detail in later sections). In typical operation, each spacecraft would collect science data and share that data with the mothership via their ISOC at fast data rates (e.g. at multi gigabit per second speeds). The mothership, in turn, receives information from all daughterships, further process it (synthesize it) and relay the post-processed data to Earth (or to another relay swarm) thru the IPN communications network.

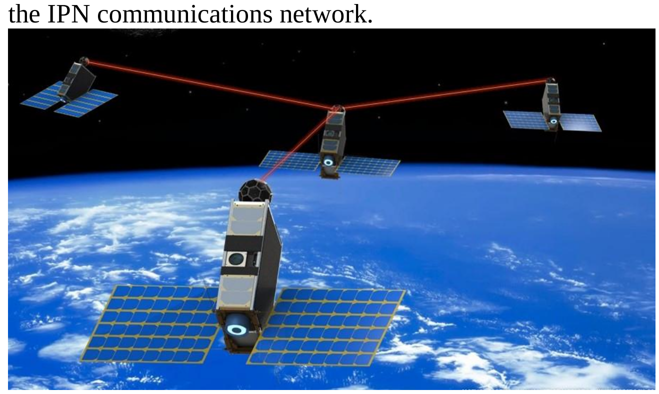

Figure 6. Swarms of spacecraft are the basis for the proposed inter-planetary network.

Intra-swarm Optical Communications

In the IPN, intra-swarm communications would be achieved using the ISOC. The ISOC is a new optical terminal being developed by JPL that provides omnidirectional coverage. It is able to offer three main capabilities: 1) high data rates, 2) full sky coverage and 3) maintain multiple links simultaneously. A key application of the ISOC is in swarms of spacecraft (Fig. 6). Other commercial applications of the ISOC include unmanned air vehicles, the Internet of Things, smart cities, etc.

The ISOC design uses a novel scheme where miniature optical telescopes on all facets of a truncated-icosahedral frame provide full sky coverage (Fig. 7). Key features of the ISOC include its high data rates and its ability to maintain multiple simultaneous links with other spacecraft.

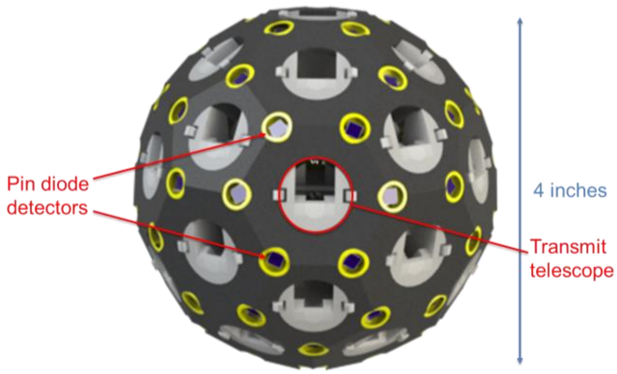

Figure 7. ISOC truncated icosahedron geometry.

The ISOC employs arrays of miniature transmit (Tx) telescopes and receive (Rx) photodetectors (Fig. 8) to provide secure high data rate communications. The Tx telescopes receive pointing commands and communications data from a field programmable gate array (FPGA) whereas the Rx photodetectors feed the incoming signals to the FPGA via suitable analog-to-digital converters (ADCs). The Tx telescopes are used to transmit the communications signals to neighboring assets. The Rx photodiodes receive optical communications signals from other spacecraft and determine the bearing and elevation of the incoming signals via a proprietary technique. Once bearing and elevation of the incoming signal is calculated by the FPGA, the ISOC can direct the appropriate telescope to communicate with the generator of the incoming signal. In this way full duplex optical communications is established.

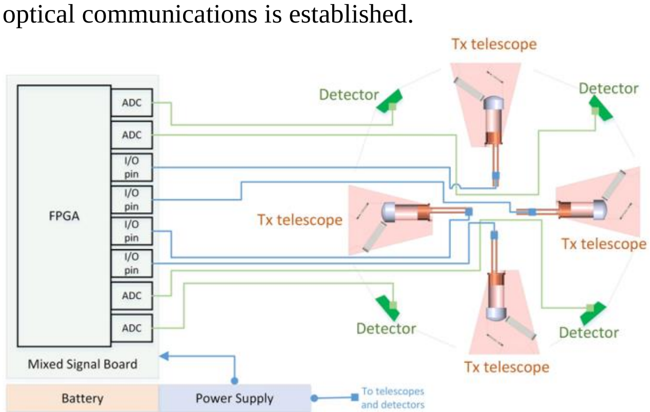

Figure 8: Simplified block diagram of the ISOC.

In Table 1 we list a set of ISOC parameters we are considering for swarm applications. Figure 9 shows plots of received power and data rate as a function of distance. Although longer intra-swarm distance may be feasible, in this case we consider a maximum distance of 1,000 km. Note that at 500 km distance between two spacecraft, the received power is $P_r = -61$ dBm and the possible data rate is $r_b = 3$ Gbps.

Table 1 - ISOC Parameters for Link Budget Calculations

Item	Units	Value
Wavelength	nm	1000
Transmit aperture diameter	mm	3.5
Receive aperture diameter	mm	5
Beam divergence angle	mrad	0.4
Transmit power	W	1
Bandwidth	GHz	2
Noise power	dBm	-64

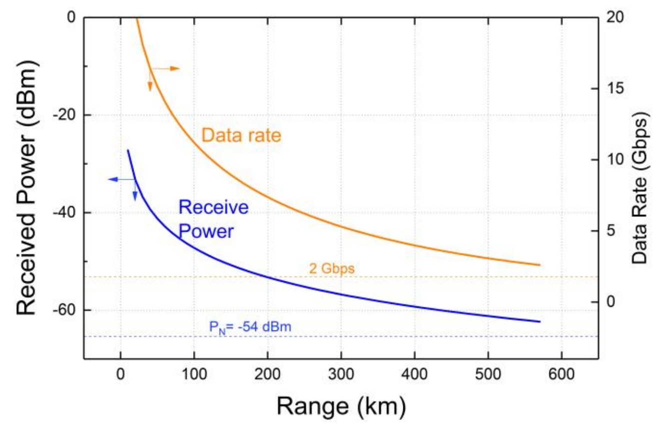

Figure 9. Plots of optical receive power and maximum data rate as a function of distance. Parameters used are listed in Table 1.

Swarm Metrology

The ISOC is a key enabling technology for the IPN. The optical beams generated by the ISOC, in addition to providing fast inter-spacecraft communications, allows for continuous swarm metrology. That is to say, the ISOC allows the spacecraft forming a swarm to continuously measure azimuth and elevation of the neighboring spacecraft. Inter-satellite distance is obtained by performing additional signal processing. Consequently, during typical swarm operation, the mothership has continuous knowledge of the position, (r, ϕ, Θ), of each spacecraft forming the swarm (Fig. 10).

Swarm Synthetic Aperture

A key feature of the IPN swarms is their ability to form a large synthetic aperture. Under this arraying arrangement, the mothership, having knowledge of the exact position of each daugthership, could send commanding information to the daugtherships that controls the phase of each ship's transmit pulse. The total swarm transmit power would be equal to the sum of each CubeSat's transmit power. On receive, the mothership could send the same synchronizing commands, so that appropriate phase shifts are applied to each spacecraft, before combining the receiving pulses.

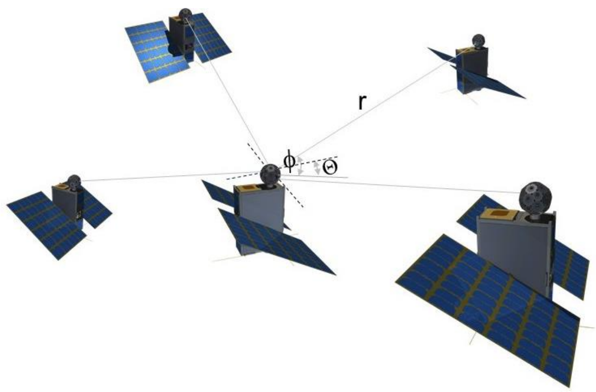

Figure 10: The ISOC allows for continuous metrology (calculation of $(\boldsymbol{r}, \boldsymbol{\phi}, \boldsymbol{\Theta})$) among spacecraft forming a swarm.

Long Range Communications

In the previous section, we described intra-swarm communications enabled by the ISOC. In this section we discuss at the potential inter-swarm (Fig. 11) data rates achievable at distances of astronomic units. For long distance communications we shall assume that each Cubesat optical transceiver is furnished with a transmit aperture D_t and with a receive aperture D_r (Fig. 5). Let's also assume that there are m and n spacecraft in the transmit and receive swarms, respectively. The total transmit power is mP_t and the received power by each spacecraft is P_r (given by Eq. 2, where P_t is replaced by mP_t), while the total power received by the swarm is nP_r. The beam divergence for each transmitted beam is still given by Eq. 4. The optical beam diameter at a distance R is $\theta_d R$. Table 2 shows a list of example parameters for $m = n = 100$, $D_t = 5$ cm, $D_r = 20$ cm, and a transmit power of 10 W per spacecraft. The diameter of the synthetic receive aperture can be calculated as $\sqrt{n}\, D_r$. Figure 12 shows plots of received power and maximum inter-swarm data rates as a function of distance. We have used Eq. 2, with mP_t as the swarm transmitted power, and $\sqrt{n}\, D_r$ as the swarm receive aperture. Note that at a distance of 1 AU ($150 \cdot 10^6$ km) between swarms, the power collected by the receive swarm is $P_r = -65$ dBm and the possible data rate is $r_b = 1.3$ Gbps.

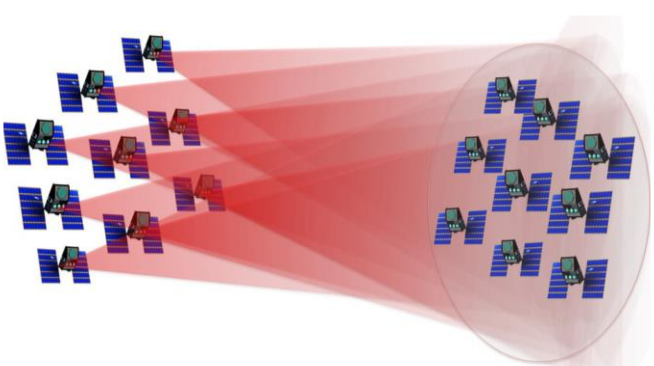

Figure 11. High data rate communications between IPN swarm nodes. Each swarm could be composed of tens of spacecraft. The distance between swarms is *R*.

Table 2 - Swarm Optical Terminal Parameters for Link Budget Calculations

Item	Units	Value
Wavelength	nm	1000
Number of Tx spacecraft		100
Number of Rx spacecraft		100
Bandwidth	GHz	1
Noise power	dBm	-67
Spacecraft		
Transmit aperture diameter	cm	5
Receive aperture diameter	cm	20
Beam divergence angle	mrad	0.02
Transmit power	W	10
Swarm		
Total Tx power	kW	1
Total Rx aperture diameter	cm	200

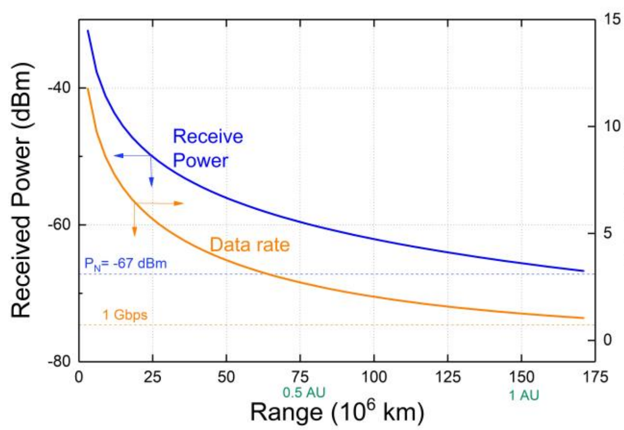

Figure 12. Plots of optical receive power and maximum data rate as a function of distance for IPN inter-swarm communications. Parameters used are listed in Table 2.

Delay Tolerant Network

Communications outside of the Internet are typically done on independent networks, each supporting specialized communication protocols. Most of these evolving networks are mutually incompatible; each is good at passing messages within its network, but not able to exchange messages between networks. Each network also has communication characteristics that are relatively homogeneous. Unlike the Internet, the evolving wireless networks experience long and variable delays, arbitrarily long periods of link disconnection, high error rates, and large bidirectional data-rate asymmetries. Examples of wireless networks outside of the Internet include: a) wireless military battlefield networks that connect troops, aircraft, satellites, and sensors on land and in water and b) inter planetary networks that may connect the Earth with other planets and space swarm stations.

The Delay- and Disruption-Tolerant Network (DTN) is a network of smaller networks [7]. It is an overlay on top of special-purpose networks, including the Internet. DTNs support interoperability of other networks by accommodating long disruptions and delays between and within those networks, and by translating between the communication protocols of those networks. In providing these functions, DTNs accommodate the mobility and limited power of evolving wireless communication devices such as the IPN. DTNs were originally developed for inter planetary use, where the speed of light can seem slow and delay-tolerance is the greatest need. DTNs may also be key for IPN's swarms, where link disruption is a key concern.

A growing number of communicating devices are in motion and operate on limited power. This is true in inter planetary space and is becoming more common on Earth among mobile wireless communication devices, such as cell phones. On the Internet, intermittent connectivity causes loss of data. Packets that cannot be immediately forwarded are usually dropped (discarded), and the Transmission Control Protocol (TCP) protocol may retransmit them with slower retransmission timing. If packet-dropping is too severe, TCP eventually ends the session, which can cause applications to fail.

The DTN, by contrast, supports communication between intermittently connected nodes by isolating delay and disruptions with the store-and-forward technique. This means that each IPN spacecraft would need to have sufficient storage capacity so that information can be held until a broken link is reestablished.

New Deep Space Ground Stations

As part of the IPN implementation, new ground complexes would be needed (similar to NASA's Deep Space Network) to cope with the throughput required by the IPN optical communications. The IPN ground complexes we envision should consist of at least two types of ground optical telescopes. Fast-moving telescopes would be needed for communications with spacecraft located in LEO and geostationary orbit. Larger (and slower) optical ground terminals could be required for deep space optical communications. Figure 13 shows an optical ground terminal that is currently under development at JPL. This ground terminal should be able to provide gigabit up- and down-link data rates for IPN spacecraft in LEO. The current design includes 40-cm diameter optical apertures which should yield multi-gigabit performance.

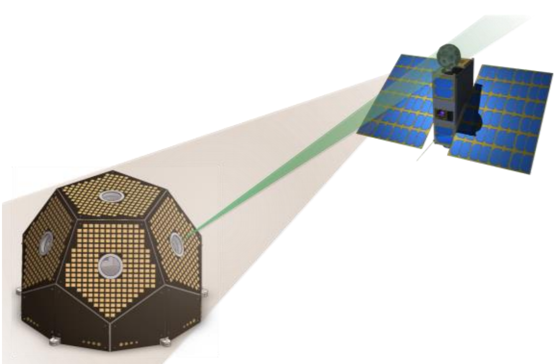

Figure 13. Optical ground terminal under development at JPL for gigabit LEO communications.

The IPN is a unique solar system platform that provides remarkable science returns. IPN CubeSat swarms are proposed to be deployed around planetary bodies and in the vicinity of their Lagrange points. This means that the inter-swarm distances could range from thousands of kilometers to portions of astronomic units. In the following sections we describe two mission concepts that could be part of the IPN: a) a cislunar IPN radio telescope and, b) an inner solar IPN system.

4. CADRE

The unexplored radio sky below ~ 10 MHz offers insight into heliophysics, planetary and exoplanetary magnetospheres, galactic magnetic fields and high energy objects as well as the early universe. Large-scale space-based interferometry is necessary to probe this regime.

In this section we present a lunar radio telescope that could be one of the initial steppingstones for IPN implementation. The radio telescope fulfills the two IPN key requirements: it is a science sensor and is outfitted for fast communications.

4.1 Radio telescope

This mission consists of a large number of small spacecraft furnished with High-Frequency (HF) observation antennas to form a large aperture radio telescope for detecting HF emissions from Exoplanets. The CubeSat Array for the Detection of RF Emissions from Exoplanets (CADRE) concept [19] involves the placement of a large swarm of CubeSats into small amplitude RFI-free Lissajous orbits around the Earth-Moon L2 Lagrange point. In addition to the HF receivers, each CADRE CubeSat is to be furnished with JPL's ISOC (see Fig. 14), which should allow data sharing at gigabit per second data rates. Unveiling the virtually unexplored HF domain with a space-based radio interferometer is very likely to lead to new scientific discoveries, as the observation of new frequency domains has done in the past. Particularly, the processes that occur in the largest physical scales and the lowest energy levels, including the cosmological Dark Ages, the epoch of reionization (EoR), solar and planetary bursts, and exoplanet RF emissions, are practically solely detectable by a low frequency interferometer array such as CADRE.

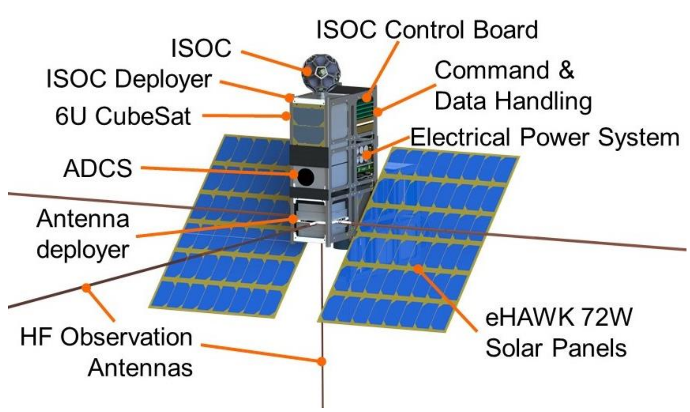

Figure 14. CADRE Cubesat [19] showing HF observation antennas and ISOC.

Radio emissions from solar system planets have been observed from both ground and space. The highest intensity emissions are those from cyclotron maser instabilities (CMIs) occurring between non-thermal electrons sourced from the solar wind and the magnetic field of the planets, which occur in the range of tens of kHz up to tens of MHz. This process is responsible for the strong terrestrial auroral emissions, and there is no reason to believe that extrasolar planets and their host stars would not have the same type of interactions. While most detection methods rely on indirect techniques, radio frequency emissions from extrasolar planets could result in new direct observations if the planet's emission dominates over the radio noise. While current methods can provide information on the exoplanet's orbital distance, orbital period, radius, and mass, none can give us any information on exoplanetary magnetic fields.

Direct detection of radio frequency emissions from exoplanets, however, could allow us to characterize this field. Furthermore, as in the case of Earth, the planet's magnetosphere may play a significant role in protecting the planetary surface from stellar wind and energetic particles, and so knowledge of the planet's magnetic field would place constraints on its habitability.

Sub-10 MHz cyclotron-maser instability emissions are likely to be the most discernible signal from Earth-like exoplanets, and could indicate the presence of sufficient magnetic field strength to shield against space weather and sustain a habitable atmosphere. However, on Earth, processes such as scintillation, ionospheric refraction and solar eruptions severely distort signals from astronomical sources below 30 MHz. Combined with the intense radio frequency interference (RFI) below 20 MHz due to manmade signals, this makes Earth-based astronomical observations in the HF domain nearly impossible. Even in space, the Earth can be a disruptive source of RFI for low-frequency observations. Auroral kilometric radiation, man-made interference and lightning can cause low frequency disturbances that interfere with the detection of transients such as exoplanet signatures. In the 1970's, the lunar-orbit RAE-2 satellite [20] observed Earth based RFI below 13.1 MHz. On the far side of the lunar orbit, shielding by the Moon provided 10-30 dB of interference suppression. Thus, the surroundings of L2 behind the moon provide a suitable RFI-free region for placement of CADRE (see Fig. 15).

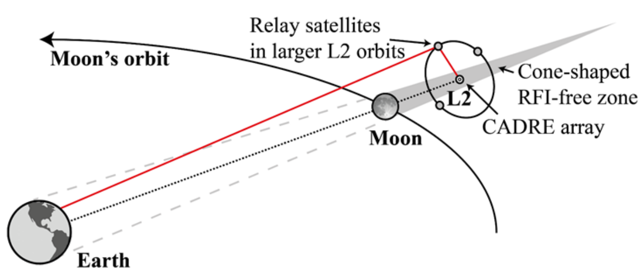

Figure 15. CADRE [19] is part of the Cislunar IPN and could be placed around L2 behind the moon. The CADRE array is located in the RFI-free zone.

The IPN CADRE mission seeks to deploy a lunar radio telescope behind the Moon (Fig. 16). With the Earth-Moon L2 orbit providing continuous RFI-free observation and the optical communicators providing unprecedented high data rate inter-satellite communications, CADRE could enable HF science goals and ultimately observe RF emissions from known exoplanets.

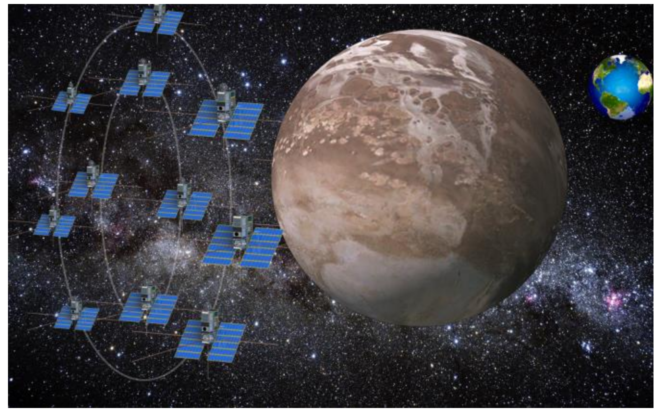

Figure 16. CADRE is a radio telescope concept that is part of the IPN [19] and located behind the moon.

4.2 Communications hub

We envision that the CADRE radio telescope could also be used as a giant array for communications. The HF receivers could be used as a receive array for HF signals located at very long distances. The optical terminals residing on each CubeSat could also be used in an arrayed fashion as a giant optical communications platform with full duplex capability.

The effective aperture of each cross-dipole antenna is given by $A_e = 1.64\,\lambda^2/(4\pi)$. Assuming an operating frequency of 1 MHz and 1,000 spacecraft on the CADRE swarm, we obtain a total receiving area of $11.75 \cdot 10^6$ m^2. For the transmit station let's assume an IPN swarm of 100 CubeSats (each furnished with HF dipoles), located around the Kuiper belt ($R = 30$ AU) and capable of transmitting 1000 watts of total power at 1 MHz. From Eqs. 1-3 we can estimate that, for a distance of 30 AU, the possible data rates between the Kuiper belt swarm and CADRE would be 1.5 Mbps. Here we have assumed a received power of $P_r = -111$ dBm and noise power of $P_n = -114$ dBm, with $B = 1$ MHz.

Another example involves using CADRE as an optical transceiver station capable of communicating with IPN swarms along the solar system. In this case CADRE's optical communicators are arrayed to act as a large optical synthetic aperture. Each CADRE ISOC has a transmit aperture of 1.5 cm and transmit power of 1 watt. Preliminary calculations for 1,000-spacecraft CADRE, with 1 kW of optical transmit power, show that CADRE could communicate with an IPN swarm (Table 2) at date rates of up to 500 Mbps at a distance of 0.5 AU.

5. INNER SOLAR SYSTEM IPN

Another IPN implementation mission could take place in the inner solar system where swarms of spacecraft can be deployed around Earth, Mars, Venus and Mercury. Placing swarms around 3 Lagrange points (L3, L4 and L5) per planet yields a total of 12 possible ISS-IPN network nodes. Figure 17 shows the inner solar system planet predicted placement for October 10, 2021. Note that under this arrangement (solar conjunction), there would be no line-of-sight between Mars and Earth for several days. This means that under this solar conjunction, no direct communications between Mars and Earth would be possible. Implementing the ISS-IPN would solve this issue, as shown in the figure. Using swarms located around Earth's L5, Mercury's L3 and Venus' L3, fast relayed communication could be kept between Mars and Earth, even during solar conjunction.

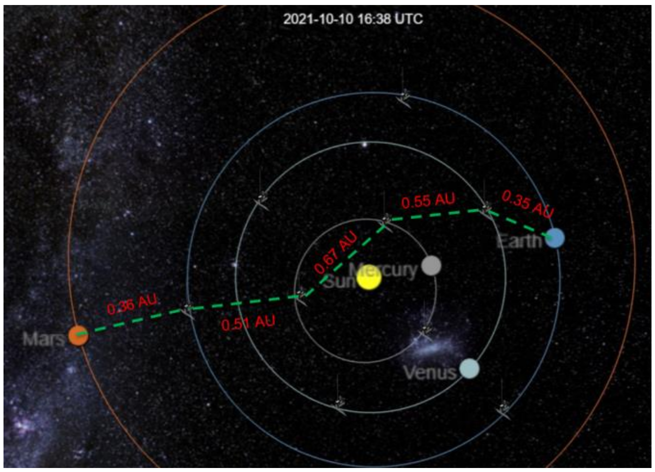

Figure 17. Swarms of spacecraft placed along the inner solar system. The shown planet alignment is a prediction for October 10, 2021 when Mars and Earth will be in conjunction. Note that the ISS-IPN allows continuous communications between Mars and Earth even during conjuction.

In Fig. 17 we also show the estimated distances between neighboring IPN swarms. Note that, based on Fig. 12 calculations, IPN swarms should be able to relay information from Mars to Earth at data rates above 1 Gbps.

6. SUMMARY

In this paper we have presented design considerations and challenges for the eventual implementation of the inter planetary network. The IPN is being proposed here as a future solar system platform that could allow for outstanding science and fast communications. The IPN is divided in three main sub-networks: cislunar IPN, inner solar system IPN and outer solar system IPN. A building block for the IPN is the use of swarms of standardized small spacecraft. Each IPN spacecraft is furnished with suitable optical communications terminals and miniature sensor payloads. Using the Shannon equations as an upper bound for data rate calculations, we have shown that data rates of 2 Gbps among spacecraft forming a swarms are possible, at distances of 500 km. Inter-swarm data rates of 1 Gbps could be possible at a distance of 1 astronomic unit using larger optical transceivers. We have also discussed the potential implementation of a large swarm of spacecraft behind the moon, to form a giant radio telescope for the detection of Exoplanets. The IPN could be implemented along the solar system in a gradual and systematic way where sorties of spacecraft could be strategically deployed along planetary Lagrange points using the inter planetary superhighways.

7. ACKNOWLEDGEMENTS

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The information presented about the IPN concept is pre-decisional and is provided for planning and discussion purposes only.

8. REFERENCES

[1] JUNO Mission to Jupiter. https://www.jpl.nasa.gov/missions/juno/

[2] InSight Mission to Mars. https://www.jpl.nasa.gov/missions/insight/

[3] The Deep Space Network. https://deepspace.jpl.nasa.gov/

[4]HITEN Mission, http://www.isas.jaxa.jp/en/missions/spacecraft/past/hiten.html

[5] Lo, M., S. Ross, "SURFing the Solar System: Invariant Manifolds and the Dynamics of the Solar System", JPL IOM 312/97, 1997.

[6] Mars Cube One (MarCO). https://www.jpl.nasa.gov/cubesat/missions/marco.php

[7] Delay Tolerant Network. http://ipnsig.org/wp-content/uploads/2015/09/DTN_Tutorial_v3.2.pdf

[8] XACT-25. https://bluecanyontech.com/components

[9] eHAWK. https://mmadesignllc.com/product/ehawk-27as112/

[10] Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA). https://www.jpl.nasa.gov/cubesat/missions/asteria.php

[11]https://www.jpl.nasa.gov/cubesat/missions/lunar_flashlight.php

[12]https://www.nasa.gov/centers/ames/engineering/projects/biosentinel.html

[13] https://www.nasa.gov/content/nea-scout

[14] https://lunahmap.asu.edu/

[15] J. E. Velazco, "Omnidirectional Optical Communicator," in IEEE Aerospace Conference Proceedings, 2019, pp. 1–6.

[16] J. E. Velazco *et al.*, "Inter-satellite omnidirectional optical communicator for remote sensing," *SPIE Opt. Eng. + Appl.*, vol. 10769, 2018.

[17] J.E. Velazco and J. Sanchez, "Q4 – a CubeSat Mission to Demonstrate Omnidirectional Optical Communications," in *IEEE Aerospace Conference Proceedings*, 2020.

[18] A. C. Aguilar, J. E. Velazco, and K. Cahoy, "Simultaneous Optical Links with the Inter-Satellite Omnidirectional Optical Communicator," in IEEE Aerospace Conference Proceedings, 2020.

[19] M. de Kok, J. E. Velazco, and M. J. Bentum, "CubeSat Array for Detection of RF Emissions from Exoplanets using Inter-Satellites Optical Communicators," in *IEEE Aerospace Conference Proceedings*, 2020.

[20] J. Alexander, M. Kaiser, F. Novaco, F. Grena, and R. Weber, "Scientific Instrumentation of the Radio-Astronomy-Explorer-2 Satellite," Astron. & Astrophys., vol. 40, no. 4, pp. 365–371, 1975.

9. BIOGRAPHY

Dr. Jose Velazco is JPL's principal investigator for the Omnidirectional Optical Communicator and has over 20 years of experience in carrying out R&D projects. Dr. Velazco has extensive experience in implementing wideband receivers for electronic surveillance applications including wide-open and superheterodyne receivers where he acquired expertise in direction-of arrival (Direction Finding) hardware and software. Recently he worked on an advanced multimegabit Optical communicator for ground application and on an all-digital phase-array radar. He is currently working on various small spacecraft mission concepts for LEO, GEO, Lunar and Deep Space applications. Dr. Velazco's current interest include the implementation of spacecraft swarms and formation flying as well as all optical spaceborne networks. He is also the technical supervisor of JPL's Advanced RF & Optical Technologies Group, which conducts advanced research and development of new RF and optical technologies and systems for new instrumentation, telecommunications and radar.